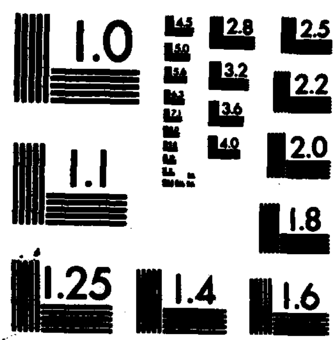
AD-A140 381 DYNAMIC FRACTURE BEHAVIOR OF STRUCTURAL MATERIALS(U) 1/1
SRI INTERNATIONAL MENLO PARK CA D A SHOCKEY ET AL.
MAR 84 AFOSR-TR-84-0262 F49620-81-K-0007

UNCLASSIFIED F/G 11/6 NL



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

SRI International

AD A140381

DTIC FILE COPY

AFOSR-TR- 84-0262

March 1984

SRI International
Third Annual Report

DYNAMIC FRACTURE BEHAVIOR OF STRUCTURAL MATERIALS

By: D. A. Shockey and J. H. Giovanola
Principal Investigators
(415) 859-2587/859-3252

Prepared for:

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
AFOSR/NE, Bldg. 410
Bolling Air Force Base
Washington, DC 20332

Attn: Dr. Alan Rosenstein

Contract AFOSR/F49620-81-K-007
SRI International Project No. PYU-2777

Approved:

G. R. Abrahamson
Vice President
Physical Sciences Division

Approved for public release; distribution unlimited.

333 Ravenswood Ave. • Menlo Park, CA 94025
(415) 326-6200 • TWX: 910-373-2046 • Telex: 334-486

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AFOSR-TR- 84-0262	2. GOVT ACCESSION NO. AD-A140 381	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) DYNAMIC FRACTURE BEHAVIOR OF STRUCTURAL MATERIALS		5. TYPE OF REPORT & PERIOD COVERED Third Annual Report Feb. 1983 to Feb. 1984
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) D. A. Shockey and G. H. Giovanola		8. CONTRACT OR GRANT NUMBER(s) F49620-81-K-0007
9. PERFORMING ORGANIZATION NAME AND ADDRESS SRI International 333 Ravenswood Ave. Menlo Park, CA 94025		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 61102F 2306/K1
11. CONTROLLING OFFICE NAME AND ADDRESS AFOSR/NE Bolling AFB, DC 20332		12. REPORT DATE March 1984
		13. NUMBER OF PAGES 15
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Fracture
Dynamic crack instability
Minimum time to fracture
Dynamic fracture toughness
Stress intensity history

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The goals of this project are to first develop and apply procedures for obtaining more accurate measures of dynamic fracture initiation and propagation toughnesses and then to establish the relationship between them. We obtain the dynamic initiation toughness, K_{Id}, by impacting unsupported edge-cracked bend specimens (one-point-bend test) and we obtain the dynamic

DD FORM 1473, 1 JAN 73 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

Block 20 (cont'd)

propagation toughness, K_{ID}, by measuring the temperature or strain histories in material near the tip of a fast-running crack.

During the third research year, the development of the one-point-bend test was completed. We demonstrated experimentally that sinusoidal stress intensity histories with a half-period varying from 90 to 450 μs can easily be obtained by varying the specimen dimensions. To correctly interpret the strain gage signal recorded during the test, we developed a simple analytical model of the experiment. The model was used to study the effect of gage position and crack propagation distance on the recorded strain history and on the ability to detect crack instability. The model was also used to investigate the mechanics of crack instability.

The dynamic fracture toughness of aircraft-quality 4340 steel (RC50) was measured using the newly developed procedure. We found that in the range of stress intensity rates from 3.3×10^5 to 3×10^6, the toughness was rate insensitive with the average value equal to 58.5 MPa $m^{1/2}$. As a consequence of this rate insensitivity, a minimum time to fracture could not be measured in the high rate tests. Based on this observation and simulations of the one-point-bend tests with the analytical model, it was concluded that the classical concepts of fracture mechanics are sufficient to make crack instability predictions for load pulse durations of tens of microseconds. However, the concept of a material-related minimum time to fracture would still have to be invoked for fracture under load pulse durations less than a few microseconds.

Future work in this program will focus on verifying these conclusions and on the parallel measurement of the propagation toughness and the initiation toughness in a VIM-VAR 4340 steel.

I SUMMARY

The goals of this project are to first develop and apply procedures for obtaining more accurate measures of dynamic fracture initiation and propagation toughnesses and then to establish the relationship between them. We obtain the dynamic initiation toughness, K_{Id}, by impacting unsupported edge-cracked bend specimens (one-point-bend test) and we obtain the dynamic propagation toughness, K_{ID}, by measuring the temperature or strain histories in material near the tip of a fast-running crack.

During the third research year, the development of the one-point-bend test was completed. We demonstrated experimentally that sinusoidal stress intensity histories with a half-period varying from 90 to 450 μs can easily be obtained by varying the specimen dimensions. To correctly interpret the strain gage signal recorded during the test, we developed a simple analytical model of the experiment. The model was used to study the effect of gage position and crack propagation distance on the recorded strain history and on the ability to detect crack instability. The model was also used to investigate the mechanics of crack instability.

The dynamic fracture toughness of aircraft-quality 4340 steel (RC50) was measured using the newly developed procedure. We found that in the range of stress intensity rates from 3.3×10^5 to 3×10^6, the toughness was rate insensitive with the average value equal to 58.5 MPa $m^{1/2}$. As a consequence of this rate insensitivity, a minimum time to fracture could not be measured in the high rate tests. Based on this observation and on simulations of the one-point-bend tests with the analytical model, it was concluded that the classical concepts of fracture mechanics are sufficient to make crack instability predictions for load pulse durations of tens of microseconds. However, the concept of a material-related minimum time to fracture would still have to be invoked for fracture under load pulse durations less than a few microseconds.

Future work in this program will focus on verifying these conclusions and on the parallel measurement of the propagation toughness and the initiation toughness in a VIM-VAR 4340 steel.

II INTRODUCTION

Structures used by the U.S. Air Force must be designed to resist catastrophic fracture when subjected to dynamic loads. For example, aircraft components may experience short stress pulses from airborne debris, military projectiles, or intense bursts of laser or x-ray radiation. Landing gear and aircraft retaining cables on carrier ships experience dynamic loads at the end of each flight.

A related dynamic fracture problem concerns rapidly running cracks. For example, it is often desirable to know whether a crack, once initiated, will arrest before it reaches a component boundary and thereby preserve the integrity of the structure. Thus, to ensure safe design of Air Force structures, it is necessary to have a knowledge of the dynamic fracture behavior of the component materials. The research being conducted in this program is aimed at improving our understanding of dynamic fracture. Emphasis is on the accurate characterization of material resistance to crack initiation under dynamic loading (K_{Id} measurements) and to rapid crack propagation (K_{ID} measurements). This annual report reviews the specific program objectives and summarizes the progress during the third research year.

K sub Id

III OBJECTIVES

To obtain more accurate measures of dynamic fracture initiation and propagation toughnesses and to establish the relationship between them, we proposed to accomplish the following research tasks in a five-year program:

Task 1 - Based on the new understanding of the role of load duration in crack instability behavior, develop a simple test procedure to obtain reliable fracture toughness values at strain rates representative of impact loading.

Task 2 - Generate the necessary data to develop a reliable theory for dynamic crack instability. In particular, measure the minimum time for instability for different K-histories.

Task 3 - Obtain values of the propagation toughness K_{ID} by means of heat of fracture or optical strain measurements and establish the relationship between K_{ID} and the dynamic fracture toughness associated with high loading rate initiation, K_{Id}.

Task 4 - Measure critical conditions and establish criteria for crack instability under mixed-mode, short-pulse loads.

This year we focused on Tasks 1, 2, and 3. The progress to date is described in the next section.

IV PROGRESS

The present program is a follow-on to a previous AFOSR-sponsored program that has provided several results that relate directly to the current work. It is therefore appropriate, before discussing the progress made during the past year, to summarize these results.

Review of Significant Results in Previous Program

In the previous AFOSR-sponsored program,[1] a crack instability theory was proposed that accounts for the influence of stress pulse duration and crack length on the dynamic stress intensity history. It was shown that well-established static stress intensity expressions apply to dynamic loading situations when the crack length, a_o, and stress pulse duration, T_o, are such that $c_1T_o/a_o > 40$ where c_1 is the longitudinal wave velocity in the specimen. On the other hand, for combinations of crack length and pulse duration satisfying the inequality $c_1T_o/a_o > 3$, the crack tip stress intensity history has a constant shape dependent only on stress pulse amplitude and independent of crack length.

To explain the results of plate impact fracture experiments (T_o = 2.04 μs) with epoxy,[2] we further postulated in the previous work that crack instability occurs only if the stress intensity exceeds the dynamic fracture toughness for a minimum (as yet, poorly defined) time.

Additional fracture experiments on 4340 steel (RC50) using single-edge notch (SEN) specimens loaded by stress pulses of several durations (18 μs to 80 μs) confirmed the important effect of stress intensity history on the onset of crack instability in structural materials. From these experiments, a dynamic fracture toughness of 31.7 MPa $m^{1/2}$ and a minimum time of 7 μs were inferred for this steel.[3]

The current program has applied the new understanding of stress intensity history effects on crack instability to the development of an impact experiment that yields unambiguous K_{Id} measurements. During the past 12 months, the development of this experiment was completed. The experiment has been used to clarify the interpretation of the minimum time to fracture and to verify the results of the previous program with a different test configuration.

Development of a New Dynamic Fracture Toughness Test

The objective of this task is to develop an easy-to-perform dynamic fracture test in which the stress intensity histories for initiation of dynamically loaded cracks can be readily controlled and fully characterized. We investigated a test configuration in which a simple edge-cracked specimen is loaded in bending by impacting it at the midsection but without supporting it at the outer edges, as is customary in other standard dynamic fracture tests. In this so-called one-point-bend test, the loading of the crack tip is achieved strictly by inertial effects. The resulting stress intensity history has approximately a sinusoidal time dependence with the period of oscillation given by the first natural frequency of vibration of the specimen. The maximum stress intensity amplitude K_{max} is controlled in part by the specimen geometry and density but mainly by the impact velocity. The stress intensity history can easily be measured during the test by placing a strain gage a short distance from the crack tip.

Test conditions suitable for dynamic fracture toughness measurements in which wave propagation effects are negligible can be achieved by using specimens with a long period (400 to 1000 μs) and by impacting at low velocities so that K_{max} only slightly exceeds K_{Id} (low K-rate experiments). This type of test can be performed on a Charpy machine. On the other hand, conditions appropriate for studying minimum time to fracture can be created by using high-impact velocities and thus by overloading the crack (high K-rate experiments). If, for the crack to become unstable, loading at or above the dynamic toughness level K_{Id} is required during a minimum time t_{min}, then crack instability in the high K-rate tests is expected to occur at a K value significantly higher than K_{Id}. The difference between the time at which the K_{Id} value is reached and the time of crack instability is a measure of the minimum time t_{min}.

During the past year, we performed a series of additional parametric experiments on specimens of varying sizes to determine the minimum stress intensity pulse duration achievable with the new test configuration. These tests showed that when the specimen dimensions are changed, half-periods ranging from about 90 to 450 μs can be obtained. They also demonstrated the strong influence of the material density on K_{max}.

To correctly interpret the strain gage signal recorded during the impact fracture test, we also developed a simple analytical model of the experiment. The model is quasi-static (no wave-crack interaction), and it assumes a sinusoidal time variation of the stress intensity factor. It also assumes that the test is displacement-controlled and uses handbook-tabulated functions to represent the change in stress intensity factor with crack length. The model is used to study the effect of gage position and crack propagation distance on the recorded strain history and on the ability to detect crack instability. It showed that for high stress intensity rates, the specimen strain at the gage location can continue to increase after the crack has started to propagate. This strain overshoot must then be taken into account when determining the point of crack initiation on the experimental records.

With this latest work, the development of the new test procedure has been completed.

Dynamic Fracture Tests to Measure K_{Id} and t_{min}

A series of impact tests were performed on aircraft-quality 4340 steel (RC50) specimens. Six tests were performed at each of three impact velocities to achieve stress intensity rates of 3.3×10^5, 5×10^5, and 3×10^6 MPa $m^{1/2}s^{-1}$. The experiments at the two lower K-rates had a loading time to fracture of well above 100 μs and hence met requirements for an unambiguous measurement of the dynamic fracture toughness K_{Id}. The tests at the highest K-rate were designed to achieve a gross overloading of the crack in order to measure the minimum time to fracture. For the tests at 3.3×10^5 MPa $m^{1/2}s^{-1}$, the crack started to propagate, then was arrested after extending 2 to 3 mm. At the higher rates, the specimens fractured completely.

The results of these series of experiments are shown in Figure 1 where the value of the stress intensity factor at the point of crack instability, K_I^{inst} is plotted as a function of the stress intensity rate, $\dot{K}$. The results in Figure 1 show that, although the scatter in data increases with the loading rate, the average values are essentially the same, 58.5 MPa $m^{1/2}$ even in the tests where the crack was grossly overloaded. Therefore, a minimum time to fracture could not be identified in these latter experiments, and the value of 58.5 MPa $m^{1/2}$ represents the dynamic fracture toughness for the material in the range of rates investigated. This value is only slightly lower than the static value K_{Ic} = 63.7 MPa $m^{1/2}$ measured in triplicate using standard ASTM E399 procedure and indicates little strain rate sensitivity of the fracture toughness of 4340 steel in the RC50 hardness condition.

This result contradicts the findings of the previous AFOSR-sponsored program in which a dynamic fracture toughness significantly lower (30-40%) than the static toughness was reported for 4340 steel (RC50). To resolve this discrepancy, we are performing additional dynamic-fracture toughness experiments on specimens cut from the broken halves of the SEN specimens tested in the previous program. Preliminary test results indicate a dynamic fracture toughness value almost double that of the one reported earlier and are consistent with the data in Figure 1; we will continue such tests in an effort to explain the differences between the results of the two programs.

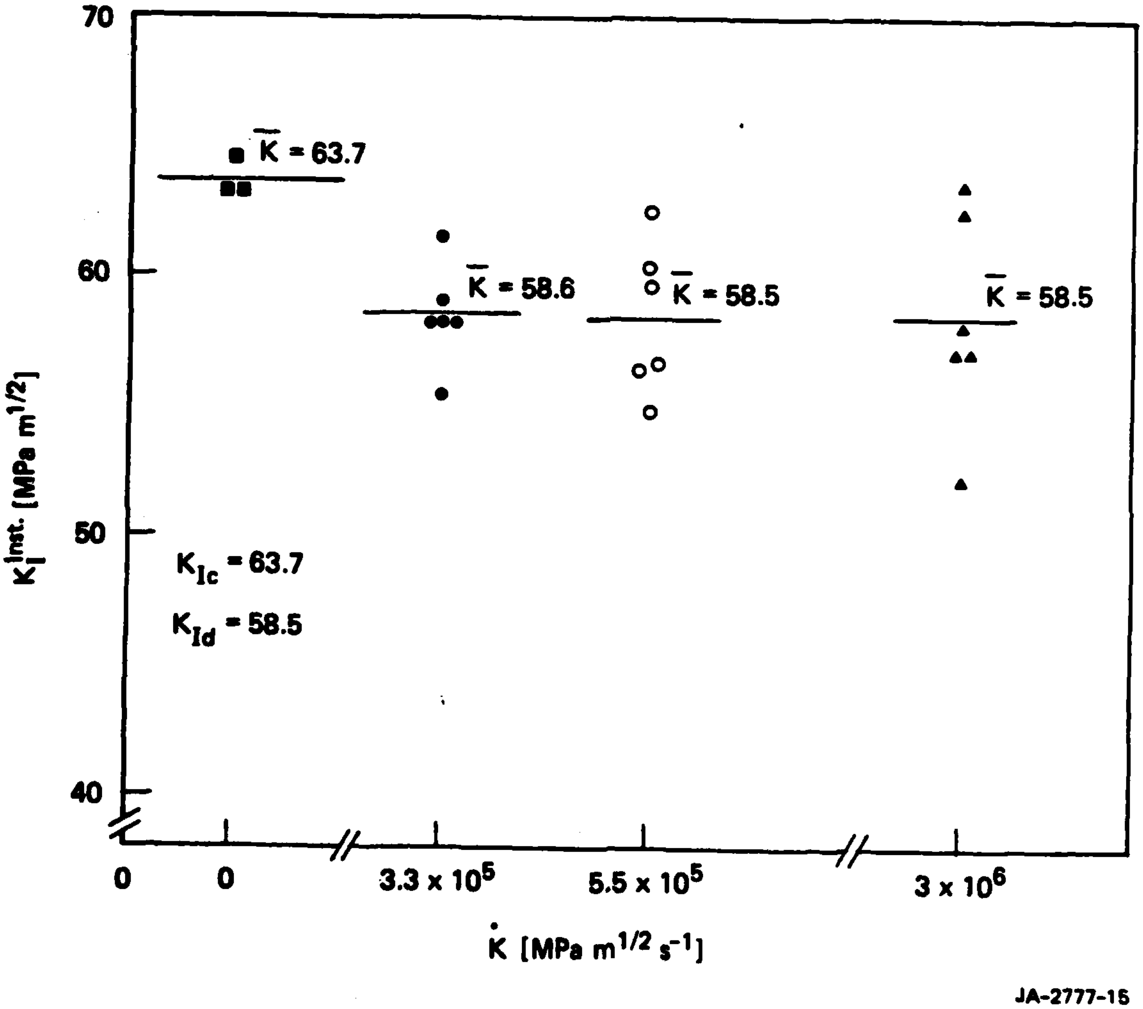


FIGURE 1 SUMMARY OF RESULTS OF DYNAMIC FRACTURE TESTS

Interpretation of the Concept of Minimum Time to Fracture

Although additional evidence is required to confirm our preliminary conclusions, the work performed during this past year has led to a better understanding of the minimum-time-to-fracture concept and to a reinterpretation of the minimum-time theory.

In considering the experimental results of the previous and the present programs, it appears that two interpretations of the minimum time to fracture are relevant, depending on the time scale over which the fracture event occurs.

For very short load durations ($T_o < 2$ μs), such as in plate impact experiments, the minimum time to fracture could be interpreted as the time required to nucleate and grow damage in the material ahead of the main crack and coalesce this damage with the main crack. In other words, the minimum time could be viewed as a material-related incubation time. Recent analytical and experimental results indicate that for metallic alloys, this time should be about 1 μs or less.[4,5]

For load durations of tens of microseconds, the material incubation time is very small compared to the load duration; hence this concept should not play a role in controlling crack instability. Rather, our recent work (in which the analytical model of the one-point bend test has been used to simulate the results of tests where crack instability and subsequent arrest have been observed) suggests that the instability conditions can be determined solely by using the classical concepts of fracture mechanics, namely, crack-driving force and material crack-growth resistance. When a minimum time to fracture is measured (as in the experiments on 4340 steel in the previous program), it could be interpreted as the time necessary to extend the crack a practically detectable distance.

V ONGOING AND FUTURE WORK

To verify the ideas pertaining to crack instability developed during the past year, we will perform a series of new experiments in which bend specimens will be impacted at increasing velocities to produce a series of crack jumps of increasing length. These results will be interpreted with the analytical model of the one-point-bend experiment and compared with the results of similar tests obtained in the previous program.

During the current year, we also plan to perform crack propagation and arrest experiments. In these experiments, the strain history near the running crack will be measured by using a new optical technique, the stereoimaging technique originally developed for strain measurements in fatigue.[6] If our attempt is successful, it will open a wide new field of strain characterization possibilities in elastic, elasto-plastic, and dynamic fracture mechanics.

We will also perform dynamic impact tests on the material used in the crack propagation tests to compare initiation and propagation toughness. Some of this work has already been initiated.

Finally, a fractographic investigation will be undertaken to try to explain the scatter in fracture toughness data, at a given stress intensity rate, in terms of differences in the microscopic fracture process.

VI PUBLICATIONS AND PRESENTATIONS

Papers prepared or published and presentations made during the previous program and under the current contract are listed below.

Publications

J. F. Kalthoff and D. A. Shockey, "Instability of Cracks Under Impulse Loads," J. Appl. Phys. 48 (3), 984-993 (March 1977).

D. A. Shockey, J. F. Kalthoff, H. Homma, and D. C. Erlich, "Criterion for Crack Instability Under Short Pulse Loads," Advances in Fracture Research, D. Francois et al., Eds., (Oxford and Pergamon Press, New York, 1980), pp. 415-423.

D. A. Shockey, J. F. Kalthoff, and D. C. Erlich, "Evaluation of Dynamic Crack Instability Criteria," Int. J. Fract. Mech. 22, 217-229 (1983).

D. A. Shockey, J. F. Kalthoff, W. Klemm, and S. Winkler, "Simultaneous Measurements of Stress Intensity and Toughness for Fast Running Cracks in Steel," Exp. Mech. 23, 140-145 (1983).

H. Homma, D. A. Shockey, and Y. Murayama, "Response of Cracks in Structural Materials to Short Pulse Loads," J. Mech. Phys. Solids 31, 261-279 (1983).

D. A. Shockey, J. F. Kalthoff, H. Homma, and D. C. Erlich, "Response of Cracks to Short Pulse Loads," Proceedings of the Workshop on Dynamic Fracture, W. G. Knauss, Ed., held at the California Institute of Technology, Pasadena, CA, under sponsorship of the National Science Foundation and the Army Research Office, Feb. 17-18, 1983.

J. H. Giovanola, "Development and Analysis of a One-Point Bend Impact Test," to be submitted for the Proceedings of the Seventeenth National Symposium on Fracture Mechanics, August 7-9, 1984, Albany, NY.

Presentations

D. C. Erlich and D. A. Shockey, "Instability Conditions for Cracks Under Short-Duration Pulse Loads," Topical Conference on Shock Waves in Condensed Matter, Meeting of the American Physical Society, Washington State University, Pullman, WA, June 11-13, 1979.

D. A. Shockey, "Instability Conditions for Cracks Loaded by Short Stress Pulses," Poulter Laboratory Seminar, SRI International, Menlo Park, CA, December 12, 1979.

D. A. Shockey, "Dynamic Crack Instability," Institut CERAC, Ecublens, Switzerland, May 19, 1980.

D. A. Shockey, "Dynamic Crack Instability," Institut für Werkstoffmechanik, Freiburg, Germany, May 21, 1980.

D. A. Shockey, "Simultaneous Measurements of Stress Intensity and Toughness for Fast Running Cracks in Steel," Poulter Laboratory Seminar, SRI International, Menlo Park, CA (June 1980).

D. A. Shockey, "Criterion for Crack Instability Under Short Pulse Loads," Fifth International Conference on Fracture (ICF5), Cannes, France, March 29-April 3, 1981.

D. A. Shockey, "Simultaneous Measurements of Stress Intensity and Toughness for Fast Running Cracks in Steel," 18th Annual Meeting of the Society for Engineering Science, Inc., Brown University, Providence, RI, September 2-4, 1981.

D. A. Shockey, "Short Pulse Fracture Mechanics," Seminar for the Department of Applied Mechanics, Stanford University, Stanford, CA, March 3, 1983, C. Steele, Chairman.

D. A. Shockey, "Short Pulse Fracture Mechanics," Poulter Laboratory Seminar, SRI International, Menlo Park, CA, April 11, 1983.

J. H. Giovanola, "Mechanics of Fracture Under Pulse Loads; Minimum Time Theory Revisited," Poulter Laboratory Seminar, SRI International, Menlo Park, CA, to be presented April 2, 1984.

J. H. Giovanola, "Development and Analysis of a One-Point Bend Impact Test," to be presented at the Seventeenth National Symposium on Fracture Mechanics, August 7-9, 1984, Albany, NY.

List of Personnel

Dr. D. A. Shockey, Principal Investigator

Dr. J. H. Giovanola, Project Leader

Mr. H. Yamada

VII REFERENCES

1. Shockey, D. A., "Fracture of Structural Materials Under Dynamic Loading," SRI Final Technical Report on Contract AFOSR/F49620-77-C-0059 (March 1981).

2. Shockey, D. A., Kalthoff, J. F., Erlich, D. L., "Evaluation of Dynamic Crack Instability Criteria," Int. J. Fract. 22, 217-229 (1983).

3. Homma, H., Shockey, D. A., Murayama, Y., "Response of Cracks in Structural Materials to Short Pulse Loads," Scan. El. Micro. 11, 79-83 (1979).

4. Curran, D. R., SRI International, private communication.

5. Clifton, R. J., Brown University, private communication.

6. Davidson, D. L., "The Observation and Measurement of Displacements and Strain by Stereoimaging," Scan. El. Micro. 11, 79-83 (1979).

END

FILMED

5-84

DTIC